

Beta-type Stirling engine operating at atmospheric pressure

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Abstract

In this study, a beta-type Stirling engine, with a 192 cc total swept-volume, was manufactured and its performance tested at atmospheric pressure. The hot-source temperature is chosen as a fundamental parameter of the experimental study. Experiments were performed with an electrical heater at 800, 900 and 1000 °C temperatures. Torque and output-power variations were obtained for different engine speeds. The test engine reached a maximum of 5.98 W at 208 rpm, at the hot-source temperature of 1000 °C.

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1. Introduction

The Stirling engine, invented in 1816 by Robert Stirling, is an externally heated engine [1]. The Stirling engine operates on a closed thermodynamic cycle with cyclic compression and expansion of the working fluid at different temperatures [2,3]. Because of its specific advantages of high efficiency, low emissions, fuel flexibility, low

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noise, low pollution and long life, Stirling engines have been attracting more and more attention in the world [1,4]. In principle, the Stirling engine is simple in design and construction, and can be operated easily [5].

Most Stirling engines of the 19th century delivered only a small power-output and were used in rural areas. A revival in the development of the Stirling engine was started by the Philips Company of the Netherlands in the 1930s. Philips was keen to open new markets for their radio sets, including remote areas in Asia and Africa. Up to the 1970s, Philips developed a number of Stirling engines with power outputs up to 224 kW [6]. In 1953, the rhombic drive mechanism was invented by Meijer [7] in Philips, Eindhoven. The primary advantage of this mechanism was that the piston applies no force to the cylinder wall and allows the use of a flexible seal between the piston and cylinder wall [8]. In 1974, the free-piston Stirling engine was invented by Beale. The phasing between the piston and displacer is not realized by a driving mechanism in this engine [9]. In a solar-energy project, undertaken by Shaltens et al. and sponsored by the US Department of Energy, two different free-piston Stirling-engines were tested. In the experimental facility, a sodium heat-pipe receiver was used. The engine manufactured by Cummins Motor Company provided efficiencies reaching 32% from light to electricity. The engine manufactured by Stirling Technology Company provided 30.7% efficiency from light to electricity [10]. Prodesser [11] developed a Stirling engine, heated by the flue gas of a biomass furnace, for electricity production in rural villages. With a working-gas pressure of 33 bars at 600 rpm and a shaft power of 3.2 kW, an overall efficiency of 25% was obtained. Dixit and Ghodke [12] designed compact power-generating systems capable of using the combination of a wide variety of solid fuels as a local power-source. The system was a heat pipe-based, biomass energy-driven Stirling engine. The macroscopic thermal design of the engine along with the calculation of various energy losses was reported. Gupta et al. [13] developed 1.0 and 1.9 kW solar-powered Stirling engines for rural applications. Engine efficiencies obtained were between 5.5% and 5.7% and overall efficiency obtained was 2.02%. In an experimental study, carried out by Hoshino et al. [14], a free-piston Stirling-engine was tested. The electric efficiency of the test facility was measured as 20%. The thermal efficiency of the experimental facility was determined as 33%.

The present study is concerned with both manufacture and performance tests of a beta-type prototype Stirling engine operating at atmospheric pressure.

2. Test engine

The schematic illustration of the experimental engine and its specifications are shown in Fig. 1 and Table 1. The engine consists of a crankcase, a crankshaft as well as a piston and a displacer situated at 90° angles to each other. Both the piston and the displacer move in the same cylinder. The piston was made of Sphero cast-iron, which includes graphite to achieve its low friction and high impact resistance. The contact surface of the piston to the surface of cylinder liner was machined to super-finish quality. A 0.02-mm working clearance was left between the piston and

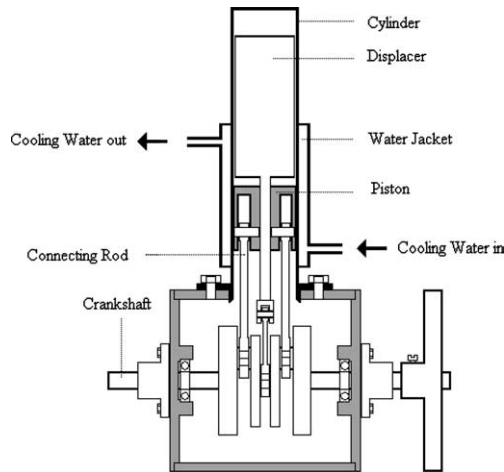


Fig. 1. Schematic illustration of the prototype test-engine.

Table 1
Technical specifications of the test engine

Engine type	Beta
Bore $\times$ Stroke (mm)	70 $\times$ 50
Swept volume (cc)	192
Phase angle	90°
Compression ratio	1.65:1
Working fluid	Air
Cooling system	Water cooled
Maximum engine power	5.98 W at 208 rpm

cylinder. The piston was connected to the crankshaft by two light duralumin rods. The displacer and its cylinder were made of ASTM steel. Between the displacer and its cylinder, a 0.6-mm gap was left for the flow of the working fluid. The inner surface of the cylinder was of super-finish quality achieved by honing and lapping. The external surface of the lower half of the displacer cylinder was cooled by housing it in a water jacket. The rod of the displacer was made of hardened AISI 4080 steel. The whole engine is shown in Fig. 2.

3. Experimental procedure

Heat was supplied by an electrical heater, NUVE, after some adaptations. The heater was adjustable to achieve any temperature between 0 and 1200 °C to 1 °C accuracy. The hot end of the cylinder was inserted into the heater A. Prony type dynamometer to 0.003 Nm accuracy was used to measure the torque. The speed of the engine was measured by a digital tachometer, DT-2234A, to 1 rpm accuracy.



Fig. 2. The test engine.

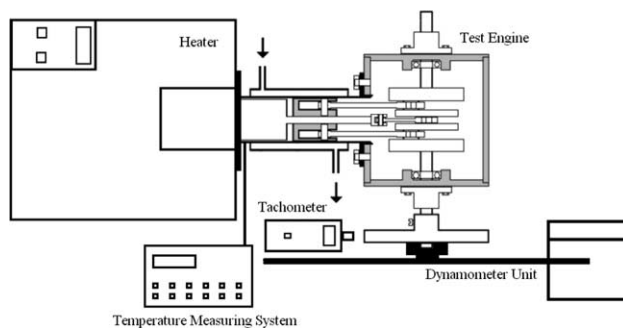


Fig. 3. Schematic view of the test equipment.

Ambient air was used as the working fluid. The lower half of the displacer cylinder was kept at 30 °C by circulating tap-water through the water jacket around it. Temperatures were measured to 1 °C accuracy via a ELIMKO-6000. The thermocouples used were of NiCr–Ni type, which can be measured up to 1200 °C. The test equipment is shown in Fig. 3.

4. Experimental results and discussion

The test engine began to run at 650 °C hot-source temperature. The test engine was run under different operating conditions during the development process. After

ensuring that no mechanical and thermal problems remained, the systematic tests were conducted to obtain the working characteristics of the engine. Systematic testing was conducted using air at atmospheric conditions and for hot-source temperatures above 800 °C. As the hot-source temperature was constant at any desired value, the speed of the engine was measured versus the engine torque. Then, the temperature of the hot source was increased by 100 °C. The hot-source temperature was varied from 800 to 1000 °C in increments of 100 °C.

Atmospheric air was the working fluid. The variations of output power and torque with engine speed are shown in Figs. 4–6. It is seen that increases in the hot-source temperature results in increases in engine speed, engine torque and

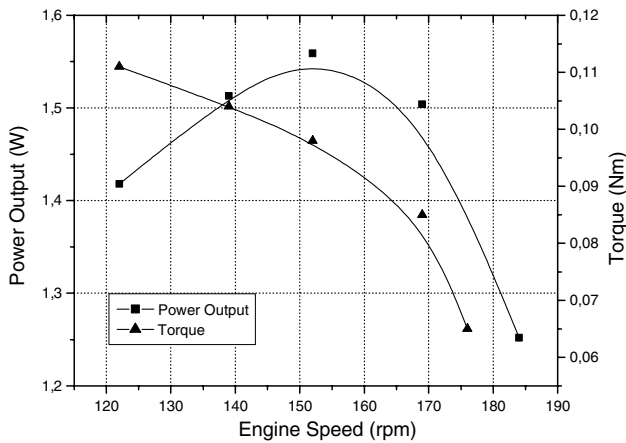


Fig. 4. Variation of brake power with engine speed at 800 °C hot-source temperature.

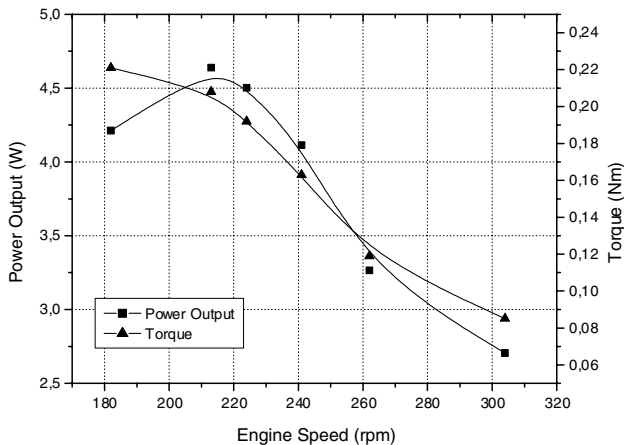


Fig. 5. Variation of brake power with engine speed at 900 °C hot-source temperature.

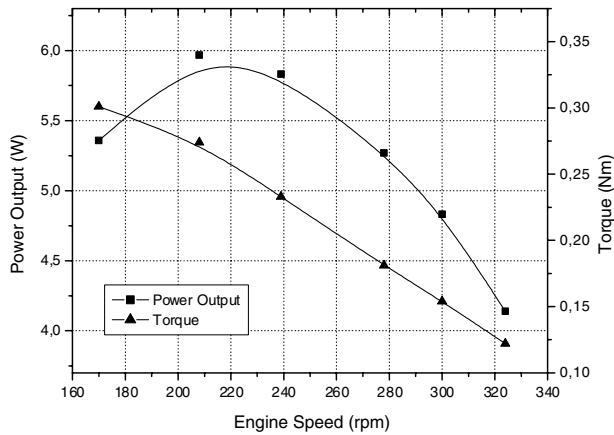


Fig. 6. Variation of brake power with engine speed at 1000 °C hot-source temperature.

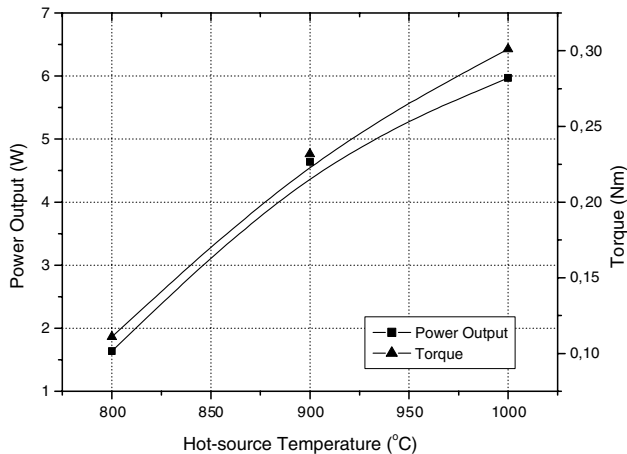


Fig. 7. Variations of brake power and torque with hot-source temperature.

power-output. The maximum engine-power was 5.98 W at 208 rpm for the hot-source temperature of 1000 °C. Since the power-output is a function of speed and torque, the lower the speed and torque, the lower the power. The decline of power after a certain speed is attributed to inadequate heat transfers.

Fig. 7 shows the output power and torque curves obtained at various hot-source temperatures from 800 to 1000 °C. The curves indicate that the output power and torque increase as functions of the hot-source temperature. Advances made in high-temperature resistant material technology will improve the performance of Stirling engines.

5. Conclusion

In this experimental study, a beta-type Stirling engine with a 192 cc total swept-volume was manufactured and tests were conducted at atmospheric pressure. An increase in the hot-source temperature results in increases in engine speed, engine torque and power-output. With an increase in the hot-source temperature, the maximum temperature of the cycle increased. The test engine provided a maximum of 5.98 W at 208 rpm, with the hot-source temperature of 1000 °C. The performance of the engine would improve at the high hot-source temperatures if better temperature resistant materials were available and the performance can be increased by the enlargement of the heater's inner surfaces. Also, the performance can be increased by using a working fluid with a higher thermal conductivity, such as helium or hydrogen, at high charge pressures in the hermetic engines.

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